Did *Swift* measure GRB prompt emission radii?

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ABSTRACT

The Swift X-Ray Telescope often observes a rapidly decaying X-ray emission stretching to as long as $t \sim 10^3$ seconds after a conventional prompt phase. This component is most likely due to a prompt emission viewed at large observer angles $\theta > 1/\Gamma$, where $\theta \sim 0.1$ is a typical viewing angle of the jet and $\Gamma \geq 100$ is the Lorentz factor of the flow during the prompt phase. This can be used to estimate the prompt emission radii, $r_{em} \geq 2tc/\theta^2 \sim 6 \times 10^{15}$ cm. These radii are much larger than is assumed within a framework of a fireball model. Such large emission radii can be reconciled with a fast variability, on time scales as short as milliseconds, if the emission is beamed in the bulk outflow frame, *e.g.* due to a random relativistic motion of "fundamental emitters". This may also offer a possible explanation for X-ray flares observed during early afterglows.

Subject headings: gamma-rays: burster

1. Introduction

Recently launched *Swift* satellite (Gehrels *et al.* 2004) together with a network of ground based observations have been providing scientific community with crucial information on Gamma Ray Bursts (GRBs). Besides the landmark detection of afterglows from short GRBs (*e.g.* Gehrels *et al.* 2005), *Swift* has gathered crucial data on developments of GRBs at early times. This is especially important since early observations provide clues to the properties of the ejecta, like its composition, lateral distribution of energy etc. At late times the energy is mostly transfered to the forward shock, properties of which can hardly be used to probe the ejecta. A number of surprising results related to early afterglows have emerged (*e.g.* Tagliaferri*et al.* 2005; Nousek *et al.* 2005; Chincarini *et al.* 2005; O'Brien *et al.* 2005): (i) early, $t \leq 10^3$ s, rapidly-decaying X-ray component, (ii) X-ray flares occurring at $t \sim 10^2 - 10^4$

s, (iii) shallower than expected initial decay (or hump) of the afterglow. These features are common, but the light curves show a large variety. In this letter we discuss the first two mentioned effects, *i.e.* rapidly-decaying component and X-ray flares, since both can be related to the prompt emission (as opposed to afterglow) and can thus be used to probe the ejecta and the central engine.

2. Prompt emission radii

The initial fast-decaying part of afterglows can be a "high altitude" prompt emission, coming from angles $\theta > 1/\Gamma$ (Kumar & Panaitescu 2000; Barthelmy *et al.* 2005), where θ is the angle between the line of sight and the direction from the center of the explosion towards an emitting point and Γ is the Lorentz factor of the outflow. For a δ-function in time prompt emission pulse, after an initial spike the observed flux should decay as $t^{-(2+\alpha)}$, where $\alpha \approx 0.5$ is prompt emission's spectral index, (Fenimore *et al.* 1998), roughly consistent with observations. One also expects that prompt and early afterglow emission join smoothly, which seems to be generally observed (O'Brien *et al.* 2005). [Exceptions, like GRB050219a (Tagliaferri*et al.* 2005), may be due to interfering X-ray flares.]

If we accept the interpretation of the fast decaying part as "high altitude" prompt emission, one can then determine radii of the prompt emission and compare them with model predictions. The currently most popular fireball model (*e.g.* Piran 2004) relates radii of emission r_{em} to the variability time scale δt of the central source $r_{em} \sim 2\Gamma_0^2 c\delta t$, where $\Gamma_0 \sim 100 - 300$ is the initial Lorentz factor. Within the framework of the fireball model this is also the variability time scale of the prompt emission. Observationally, prompt emission shows variability on time scales as short as milliseconds, while most power is at a fraction of a second (Beloborodov *et al.* 1998). Adopting $\delta t \sim 0.1$ s, the prompt emission radius is $r_{em} \sim 6 \times 10^{13}$ cm $(\Gamma_0/100)^2$. If the emission is generated at r_{em} and is coming to observer from large angles, $\theta > 1/\Gamma$, its delay with respect to the start of the prompt pulse is $t \sim (r_{em}/c)\theta^2/2$. If one can estimate θ, then this can be used to measure r_{em}. This can be done from late "jet breaks", giving typically $\theta \sim 0.1$ (*e.g.* Frail *et al.* 2001). Then, for the X-ray tail of the prompt emission extending to $t \sim 1000$ seconds, the implied emission radius is $r_{em} > 6 \times 10^{15}$ cm. This is much larger than is assumed in the fireball model. To make it consistent with the fireball model and variability on short times scales, the Lorentz factor of the flow should be huge, $\Gamma_0 \geq 1000$, but this would imply that emission is strongly de-boosted, $\Gamma_0\theta \sim 100$. Increasing θ cannot save the day either since the required viewing angle would be $\theta \sim 1$, implying a jet moving always from an observer.

Along the similar lines of reasoning, Lazzati & Begelman (2005) estimated prompt

emission radii for a particular case of GRB 050315 for which a possible jet break is identified (Vaughan *et al.* 2005) . Steep decay in that case is relatively short and lasts for 100 s, giving $r_{em} > 2.5 \times 10^{14}$ cm. Note, that any observed duration of the steep decay phase provides only *a lower limit* on the prompt emission radius since the end of the steep decay may be related to emergent afterglow emission and not to the fact that the edge of the jet becomes visible, see Fig. 1. On the other hand, late jet break time provides an estimate of the total opening angle of the jet. In any case, GRBs with longer lasting steep decay phase, up to 10^3 s, provide the most severe constraints on the models.

Thus, the interpretation of the fast-decaying initial X-ray light curve as prompt emission seen at large angles can hardly be inconsistent with the fireball model. We should then either look for alternative possibilities to produce the fast-decaying part of the X-ray light curve (*e.g.* Mészáros & Rees 2001), or consider models that advocate production of prompt emission at larger radii, see §5.

3. Fast variability from large radii

If prompt emission is produced at distances $\sim 10^{15} - 10^{16}$ cm, how can a fast variability, on times scales as short as milliseconds, be achieved? One possibility, is that emission is beamed in the outflow frame, for example due to a relativistic motion of (using pulsar physics parlance) "fundamental emitters" (Lyutikov & Blandford 2003). To prove this point, we consider an spherical outflow expanding with a bulk Lorentz factor Γ with N randomly distributed emitters moving with respect to the shell rest frame with a typical Lorentz factor γ_T. Highly boosted emitters, moving towards an observer, have a Lorentz factor $\gamma \sim 2\gamma_T\Gamma$ in the observer frame. If emission is generated at distances r_{em}, the observed variability time scale can be as short as $\sim (r_{em}/c)/2\gamma^2 \approx (r_{em}/c)/8(\gamma_T\Gamma)^2$, so that modest values of $\gamma_T \sim 5 - 10 \ll \Gamma \sim 100 - 300$ would suffice to produce a short time scale variability from large distances $r_{em} \sim 10^{15} - 10^{16}$ cm.

The model should satisfy a number of constraints. First, the number of sub-jets directed towards an observer from viewing angles $\theta < 1/\Gamma$ should be larger than unity (in order to produce at least one true prompt emission spike), but should not be too large, otherwise prompt emission will be a smooth envelope of overlapping spikes. If a typical jet opening angle is θ_j, then the number of sub-jets seen "head-on" from angles $< 1/\Gamma$ is

$$n_{prompt} \sim \frac{\pi N}{(\Gamma\gamma_T\theta_j)^2}. \tag{1}$$

This should be larger than 1.

The second constraint that the model should satisfy relates to the efficiency of energy conversion. Suppose that the thickness of an outflowing shell in its rest frame is $L_{shell} \sim t_s c\Gamma$, where t_s is a source activity time ($t_s \sim 30 - 100$ s for long bursts and $t_s \sim 1$ s for short bursts). Suppose then that fundamental emitters operate for a time $t_{pulse} = \eta_t L_{shell}$ in the flow frame, where η_t is a dimensionless parameter. During this time the source can tap into energy contained within volume $(ct_{pulse})^3$. The ratio of this volume times the number of emitters to the total volume of the shell is a measure of efficiency of energy conversion into radiation:

$$\eta = \frac{N(ct_{pulse})^3}{r_{em}^2 \theta_j^2 t_s c\Gamma} \tag{2}$$

Since tapping of energy in the volume $(ct_{pulse})^3$ is a definite upper limit on conversion efficiency, in the calculations we allow η defined above to be slightly larger than unity.

To produce light curves we calculate the intensity of emission from sub-jets that are randomly located within the shell and moving in random direction with random Lorentz factors $1 < \gamma_T < \gamma_{T,max} = 5$. Each emitter is isotropic in its rest frame and is active for a random time $0 < t'_{em} < \eta_T t_s c\Gamma = t_{pulse,max}$ with $\eta_T = 0.5$. The observed intensity of emission from each sub-jet $\propto \delta^{3+\alpha}$ (Lind & Blandford 1985), where $\delta = 1/\gamma(1 - \beta\cos\theta_{sj})$ is a total Doppler factor including bulk and random motion, θ_{sj} is an angle between the line of sight and direction of the sub-jet motion. As the burst progresses, larger angles and more of sub-jets producing prompt emission become visible. Most of them will be seen from angles $> 1/\gamma_T$ in the bulk frame, producing a combined smooth curve overlaid with spikes. The average Doppler factor decreases with time $\delta \approx t_s\Gamma/t$ and the average flux decays as $t^{-(2+\alpha)} \approx t^{-2.5}$ for $\alpha = 0.5$. In Fig. 1 we plot an example of a prompt light curve in this model.

3.1. Lateral dependence of prompt emission

Variations of the decay rate from the $t^{-(2+\alpha)}$ law may be used to probe angular dependence $L(\theta_{axis})$ of the intensity of the prompt emission, where θ_{axis} is an angle between the axis of the explosion and an emitting point. More shallow decays can be due to, *e.g.* , a structured jet, with $L \sim \theta_{axis}^{-2}$ observed outside of some core: late time emission then is coming from the more energetic core part. The effective emission intensity increases approximately as $\theta^2 \propto t$, and will result in an observed decay $t^{-(1+\alpha)}$. Similarly, if the prompt emission is seen within a core, late emission comes from less energetic wings, giving in case of a structured jet a flux $\propto t^{-(3+\alpha)}$. Qualitatively, the relativistic internal motion of emitters makes it "easier" to see the high altitude emission.

To show this numerically we parameterize the *number density of emitters* as $n(\theta) \propto 1/(\theta^2 + \theta_0^2)$, where θ_0 is an angular core radius. [There are, naturally other possible parameterizations, e.g. of intensity of each emitter]. The results are presented in Fig. 2.

We can also expect deviations from a simple power-law decay due to not exactly spherical form of the emitting surface. Such distortions are expected due to a development of the Kelvin-Helmholtz instability during an accelerating phase of the outflow. They won't be erased during the coasting stage due to causal disconnection of the flow separated by angles $> 1/\Gamma$. Additional complications may come from the way the data analysis is performed, *e.g.* through a choice of initial time trigger (Zhang *et al.* (2005), see also Lazzati & Begelman (2005)).

4. Origin of X-ray flares

Early X-ray light curves show complex behavior with flares and frequent changes in a temporal slope (*e.g.* O'Brien *et al.* 2005). Flares show very short rise and fall times, much shorter than observation time after the on-set of a GRB, while the underlying afterglow has the same behavior before and after the flare (Burrows *et al.* 2005) (though there are exceptions). Both of these observations argue against a physical process in the forward shock. In addition, there is a hardening of the spectrum during X-ray flares (Burrows *et al.* 2005).

In the present model we interpret X-ray flares as been due to sub-jets located at large viewing angles, $\theta > 1/\Gamma$, but directed towards an observer. Randomly located, narrow spikes are clearly seen in the model light curves, Figs. 1-2. In addition, as the flares are less de-boosted than the average high altitude outflow, they will have a harder spectrum, as observed.

5. Discussion

In this letter we first point out that the interpretation of the initial fast-decaying part of the X-ray GRB light curves as a prompt emission seen at large angles, and a generic estimate of jets' opening angle allows a measurement of the radius of prompt emission, which turns out to be relatively large, $> 10^{15}$ cm. On basic grounds, γ-ray emission should be generated before the deceleration radius $r_{dec} \sim \left(\frac{E_{iso}}{4\pi\rho c^2\Gamma_{dec}^2}\right)^{1/3} \sim 10^{16} - 10^{17}$ cm, when most energy of the outflow is given to the surrounding medium (here E_{iso} is isotropic equivalent energy, ρ

is density of external medium, Γ_{dec} is Lorentz factor at r_{dec}). [1] The inferred emission radius is within this limit.

The estimate of the emission radius is very simple, and, in some sense, generic. It can hardly be consistent with the fireball model, unless extreme assumptions are made about the parameters (*e.g.* very large Lorentz factor). On the other hand, there are alternative models (*e.g.* the electromagnetic model (Lyutikov 2005b), see also Thompson (2005)) that place prompt emission radii at large distances, just before the deceleration radius r_{dec}.

Secondly, we show how models placing emission at large radii may be able to reproduce a short time scale variability of the prompt emission and explain later X-ray flares. This can be achieved if the prompt emission is beamed in the rest frame of the outflow, which may be due to an internal relativistic motion of "fundamental emitters".

What can produce a relativistic motion in the bulk frame? It can be due, for example, to a relativistic Burgers-type turbulence (a collection of randomly directed shock waves). It is not clear how such turbulence may be generated. Alternatively, relativistic internal sub-jets can result from reconnection occurring in highly magnetized plasma with $\sigma \gg 1$, where σ is a plasma magnetization parameter (Kennel & Coroniti 1984). In this case the matter outflowing from a reconnection layer reaches relativistic speeds with $\gamma_{out} \sim \sigma$ (Lyutikov & Uzdensky 2003). Internal synchrotron emission by such jets, or Compton scattering of ambient photons, will be strongly beamed in the frame of the outflow. Note, that *this model does not require late engine activity* to produce flares.

One of the main observational complications is that at observer times larger than the conventional prompt phase, the X-ray light curve is a sum of the tail of the prompt emission, coming presumably from internal dissipation in the ejecta, and the forward shock emission. It is not obvious how to separate the two components. For example, GRBs which do not show a fast initial decay may be dominated by the forward shock emission from early on (O'Brien *et al.* 2005). This uncertainty also affects estimates of the emission radius since the end of the steep decay may be related to the emergent afterglow emission and not to the jet opening angle (or observer's angle, in case of a structured jet), see Fig. 1. Another complication is that at these intermediate times, $10^3 \leq t \leq 10^4$ s, even the forward shock emission itself often does not conform to the standard afterglow models, showing flatter than expected profiles (*e.g.* Nousek *et al.* 2005).

A consequence of the model is that *some* short GRBs may be just a single spike directed

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[1] Note, that r_{dec} defined above is *independent* of ejecta content, contrary to the claim in Zhang & Kobayashi (2005), see Lyutikov (2005a).

towards an observer of a long GRBs. In our model the shorter spikes are highly beamed, less frequent and produce harder emission. This can apply only to *some* short GRBs since as a class they are well established to have different origin than long GRBs (from non-observation of a supernova signature and coming from a distinctly different host galaxy population).

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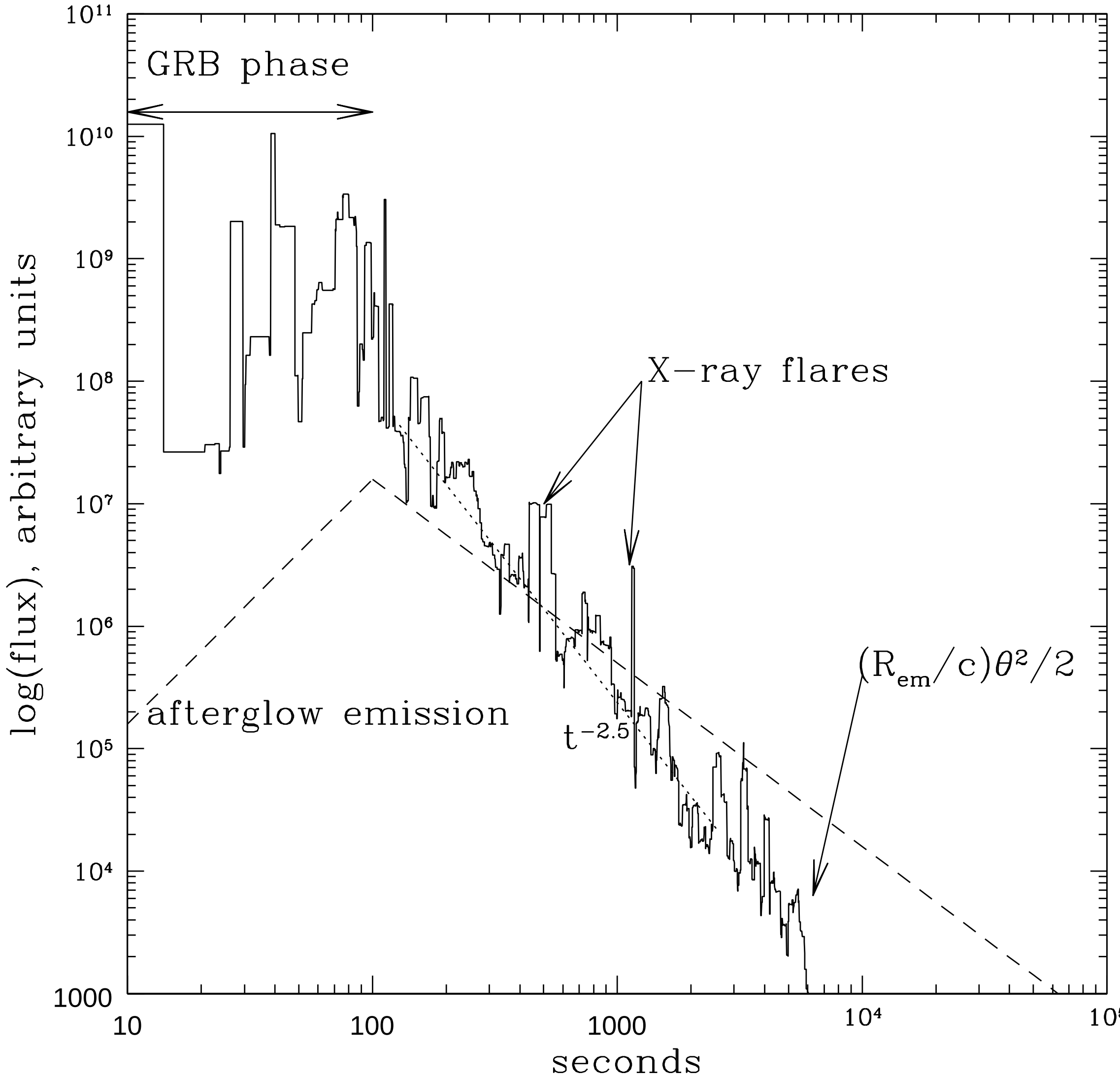

Fig. 1.— Prompt emission produced by emitters moving randomly in the bulk frame. Emission is generated within a shell of thickness $t_s c = 3 \times 10^{12}$ cm in observer frame, moving with $\Gamma = 100$ at distance $r_{em} = \Gamma^2 t_s c$ by randomly distributed sub-jets with random orientation moving with random Lorentz factors $1 < \gamma_T < \gamma_{T,max} = 5$. Each emitter is active for random time $0 < t'_{em} < 0.5 t_s c \Gamma = t_{pulse,max}$ in its rest frame. Dotted line: average intensity $\propto t^{-(2+\alpha)} = t^{-2.5}$. Dashed line: expected afterglow signal rising $\propto t^2$, peaking at ~ 100 s and falling off $\propto t^{-1.5}$ with arbitrary normalization. Homogeneous jet centered on an observer with opening angle $\theta = 0.1$, dimensionless parameters are $n_{prompt} = 1.2$ and $\eta = 1.6$.

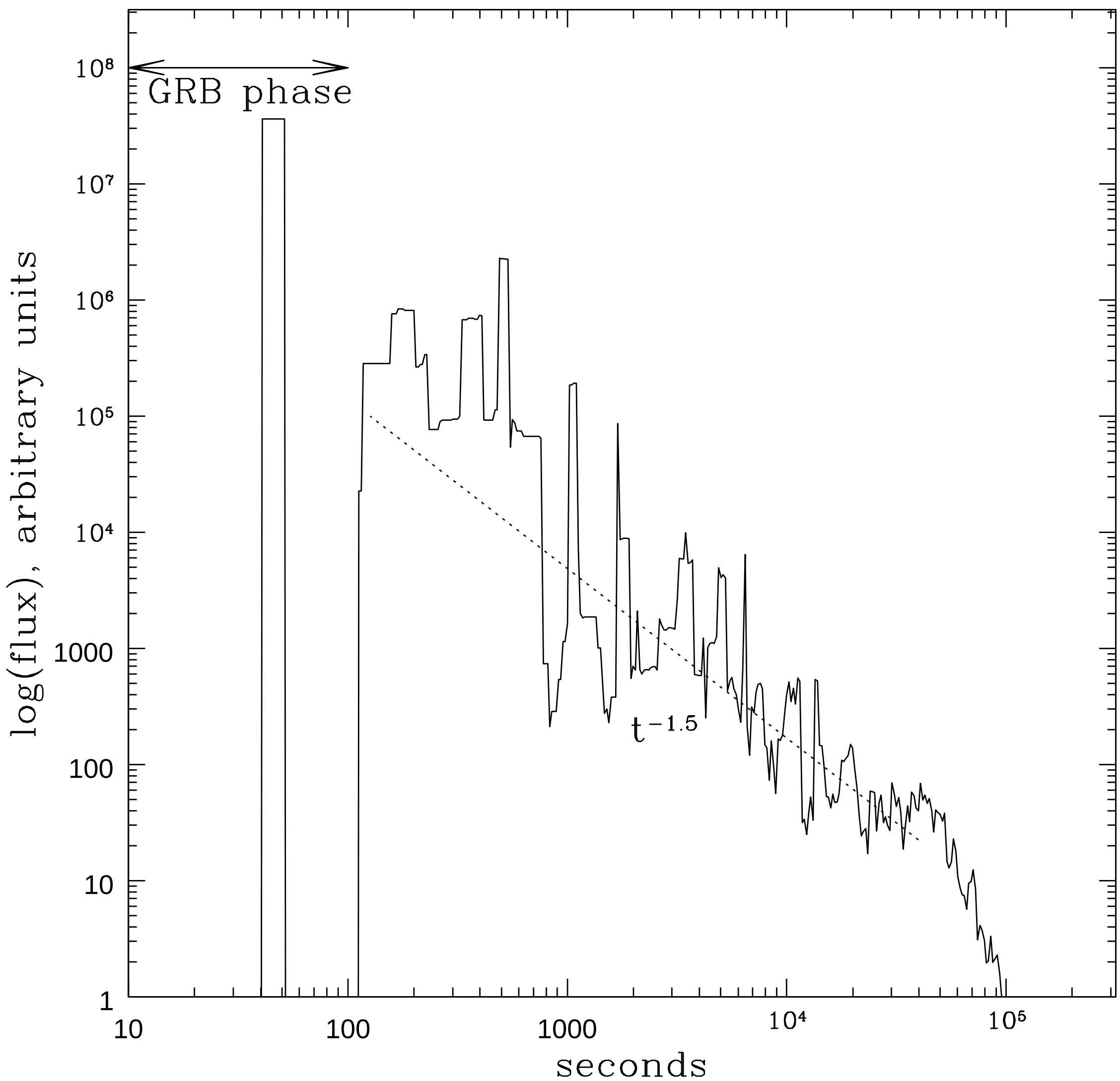

Fig. 2.— Same as Fig. 1 for structured jet with number density of sub-jets $\propto 1/(\theta^2 + \theta_0^2)$, core size $\theta_0 = \pi/100$, observer angle $\theta_{ob} = \pi/10$, dimensionless parameters are $n_{prompt} = 1.26$, $\eta = 1.6$ (calculated with $\theta = \theta_{ob}$).